RAPID AND ACCURATE DETERMINATION OF SERIES RESISTANCE AND FILL FACTOR LOSSES IN INDUSTRIAL SILICON SOLAR CELLS

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ABSTRACT: Lower than ideal fill factors (FF) are caused by parasitic series (R_s) and shunt (R_{shunt}) resistances, and non-ideal diode properties. The challenge is to quantify the FF losses quickly, simply and without ambiguity. Extracting the parameters by fitting the illuminated or dark measured data with the double diode equation is inaccurate since the externally apparent R_s is not constant; it varies with illumination level and electrical load. It is shown that the variations in R_s are not a second order effect only noticeable in laboratory cells, but that the variations are even more important in industrial solar cells and many methods underestimate R_s. It is also common to estimate the cause of FF loss by visual inspection of the IV curve, but this also leads to a misinterpretation of loss mechanisms. A very high R_s affecting 10% of the cell causes a slope at short circuit current that is very similar in appearance to a cell with low R_{shunt}, and that a high R_s affecting 50% of the cell appears similar to high second diode saturation current. A superior method to measure R_s at the maximum power point is to shade the cell to 0.1 suns and measure open circuit voltage and short circuit current. Using this extra data with standard one sun measurements also measures the average diode ideality factor, R_{shunt}, and reveals non-ohmic contacts.

Keywords: Characterization – 1: Modelling – 2: Series Resistance – 3.

1. INTRODUCTION

The fill factors (FF) of commercial solar cells are lower than ideal primarily due series resistance (R_s), which will become larger as substrate size increases. However, in both laboratory and production cells, the fill factor is not solely limited by the R_s but also by effects such as low shunt resistance and non-ideal diode parameters. Separating out the effects of the various losses is essential for diagnosing fabrication problems. A cell production line additionally requires a very fast measurement of the cell parameters if they are to be at all useful. Ideally such methods would be taken from the one sun IV curve so that no extra measurements need to be taken. However, the one sun illumination curve alone has insufficient data to separate out the losses [1].

2. CURVE FITTING TO DARK AND ILLUMINATED IV CURVES.

Simple one-dimensional models of solar cells (such as PC1D) have a single constant resistor in series with the cell, as shown in Figure 1.

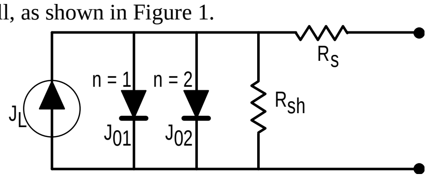

Figure 1: Double diode model of the cell.

The cell in Figure 1 is described by the following equation when illuminated. The extra –1 terms of the ideal diode equation are irrelevant at the current levels involved.

$$J = J_L - J_{01} \exp\left(\frac{q(V + JR_s)}{kT}\right) - J_{02} \exp\left(\frac{q(V + JR_s)}{2kT}\right) - \frac{V + JR_s}{R_{shunt}}$$

In the dark, J_L is equal to zero, the current flows into the cell and the equation is:

$$J = J_{01} \exp\left(\frac{q(V - JR_s)}{kT}\right) + J_{02} \exp\left(\frac{q(V - JR_s)}{2kT}\right) + \frac{V - JR_s}{R_{shunt}}$$

Using the equations it should be possible to fit the measured data to extract the parameters R_s, R_{shunt}, J_{01} and J_{02} assuming they are constant. Parameter fitting has been done with various levels of sophistication to improve extraction speed and to cope with the effects of measurement noise: see [2] [3] and references therein. However, R_s is not constant but is a function of J, an effect even more pronounced in commercial cells. This leads to errors in extraction as shown below.

3. MODELLING THE EFFECT OF DISTRIBUTED SERIES RESISTANCE

The externally seen R_s of a solar cell is composed of a variety of internal resistances. In a typical commercial solar cell the dominant resistances are: contact resistance (R_c), resistance of the busbars (R_{bb}), finger resistance (R_f), and lateral conduction in the emitter, ($R_{emitter}$). For screen-printed cells, the contribution of the rear contact is minimal due to the full metal coverage and low base resistivity. The relative importance of each resistor is dependent on the current flow in the cell. If the current paths were identical at all bias levels it would be possible to describe R_s by a single constant value. However a cell is a network of diodes and resistors causing variations in the path the current flows, which produce variations in the externally measured R_s. The fraction of current flowing through a resistor determines its contribution to the externally measured R_s. In commercial silicon solar cells, points near the contact pads will have a much lower R_s than those at the end of high resistivity screen-printed fingers. Processing errors with breaks in fingers or incompletely printed sections further increase the distributed nature of R_s.

To examine the effects of distributed R_s, a model described below is used where part of the cell is affected by R_s and part of the cell is not. There exist more complicated models for distributed R_s [4] but the model used here simplifies the discussion.

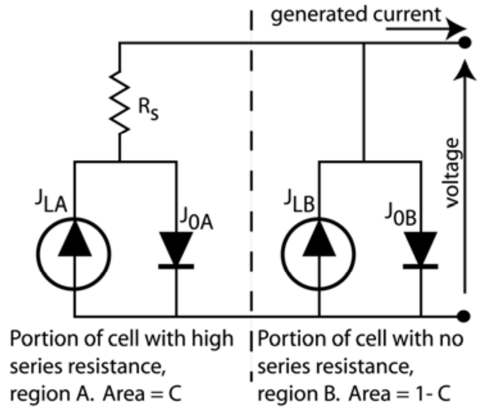

Figure 1: solar cell in which only part of the cell is affected by R_s. In the dark the J_L elements are removed and the current direction is reversed so it flows into the cell.

In the model of Figure 1, R_s affects only part of the cell. The proportion of the cell affected by the high R_s is denoted by C. Varying C between zero (no part of the cell affected by R_s) and one (all the cell is affected by R_s) shows how a distributed R_s affects final IV curve. The two diodes are identical with J_{01} of 1.5×10^{-12} A/cm² and a J_{sc} of 35 mA/cm². The corresponding currents are adjusted according to the area specified by C. To further simplify the discussion R_{shunt} and J_{02} are set to zero. Setting R_s to zero gives the ideal cell curve without the effects of R_s. The cell R_s at each current level is calculated from the difference between the curves as shown in Figure 2.

3.1. R_s affects entire cell

The simplest case is where R_s affects the entire cell so that C = 1 and the elements of region B are removed.

	R_s (Ωcm²)	J_{01} (A/cm²)	J_{02} (A/cm²)
Actual	1	1.5e-12	0
Illuminated fit	0.998	1.51e-12	0
Dark fit	1	1.5e-12	0
Dark/Light difference	1	-	-

The table above shows that with C = 1 the model reduces to the traditional example with a constant R_s. In this case the R_s is constant for both the illuminated and dark cases at 1 Ω.

The "Dark/Light difference" measures R_s from:

$$R_s = \frac{V_{dark}(I_{sc}) - V_{oc}}{I_{sc}},$$

where $V_{dark}(I_{sc})$ is the voltage of the cell in the dark at a current level equivalent to I_{sc}.

3.2. Series resistance appears like high J_{02}.

The next case considered is where a large section of the cell is affected by a high R_s. This corresponds to a cell with wide finger spacing and a high emitter sheet resistivity. Portions near the fingers will have much lower R_s that those equidistant from the fingers. The points show the double diode fit. While the double diode equation fits the curve accurately it does not correctly describe the physical mechanisms within the cell.

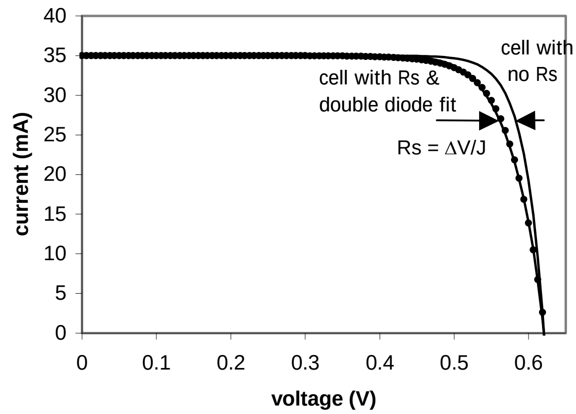

Figure 2: Cell with a medium R_s affecting half the cell (R_s = 3 Ω, C = 0.5). The rounding at the maximum point appears very similar to a cell with a high J_{02} yet it is caused solely by R_s.

The actual R_s is calculated from the voltage difference between the ideal curve and the R_s affected curve at each current level as shown below. Also shown is the R_s in the dark case.

The effect of distributed R_s is quite different in the dark and light cases. In the light case the current is generally generated uniformly across the device and must be conducted to the contacts. In the dark case the current is conducted along the most favourable conduction path. Regions of higher resistivity (a section that is not printed or regions between the contacts) are bypassed so the apparent R_s seen externally is much lower in the dark case than in the illuminated case. Additionally in the dark case the region of the curve that is affected by R_s is a different region of the curve to that affected in the illuminated case.

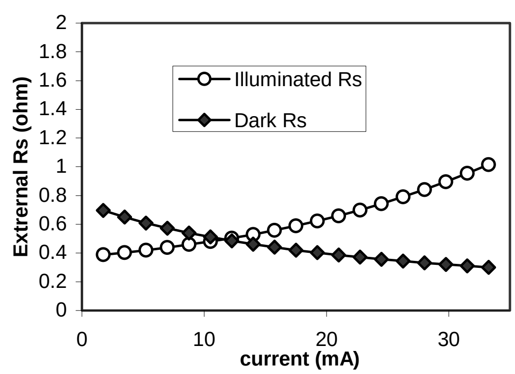

Figure 3: The internal resistance is constant but varies externally. I_{mp} = 33 mA/cm².

	R_s (Ωcm²)	J_{01} (A/cm²)	J_{02} (A/cm²)
Actual	1	1.5e-12	0
Illuminated fit	0.54	1.1e-12	4.8e-12
Dark fit	0.2	1.5e-12	0
Dark/Light difference	0.16	-	-

3.3. R_s Appears Like Low R_{shunt}.

Another possibility is where a very high resistance affects a small portion of the cell but the rest of the cell is relatively unaffected. This happens where there is incomplete printing with interruptions in the grid lines or areas of the cell where there is no metallisation at all.

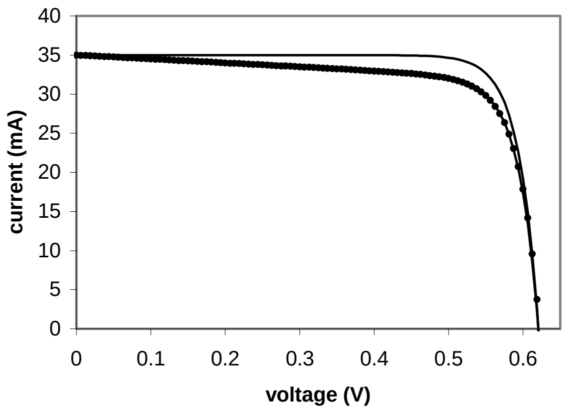

Figure 4: Cell with a high R_s affecting a small portion of the cell (R_s = 150 Ω, C = 0.1). The resulting IV curve looks just like a cell with a low R_{shunt} but again the effect is due solely to Rs. J_{mp} = 30 mA/cm²

The double diode fit in the above curve gives R_s = 0.01 Ω, J_{01} 1.2e-12, J_{02} = 1.5e-8 A/cm². R_{shunt} =200 Ωcm². Despite being affected solely by R_s the curve is very similar in appearance to that affect by a low R_{shunt}.

	R_s (Ωcm²)	J_{01} (A/cm²)	J_{02} (A/cm²)
Actual	1.1	1.5e-12	0
Illuminated fit	0	1.2e-12	1.5e-8
Dark fit	0.0013	1.4e-12	7e-14
Dark/Light difference	0.06	-	-

4. MEASURING THE IV CURVE WITHOUT R_S

Given the problems with determining R_s from fitting routines, an alternative is required that measures R_s at the maximum power point. The simplest are the J_{sc} V_{oc} curve[5][6] or the Suns V_{oc} curve[7]. These are equivalent so long the cell J_{sc} is proportional to the light intensity, a situation that is commonly true and easily verified.

The $J_{sc}V_{oc}$ curve relies on the principle of superposition, i.e. that in the absence of R_s the illuminated IV curve is simply the dark diode curve shifted by J_{sc}. Additionally the cell V_{oc} and J_{sc} are unaffected by R_s. V_{oc} is unaffected by R_s since no current is drawn. For the current, as long as the R_s is less 10 Ωcm² there is no affect from R_s on J_{sc} [8]. While the J_{sc} V_{oc} curve is not influenced by R_s it is still affected by R_{shunt} and J_{02}.

5. PRACTICAL IMPLEMENTATION

A measurement system requires speed, reliability and simplicity. There are a number of variations depending on the specifics of the system and the degree of automation required.

5.1. Measurement of Series Resistance

To add to an existing system that already measures the full IV curve, all that is needed is to shade the cell to about 10% light intensity and then measure the cell $I_{sc\ (shaded)}$ and $V_{oc\ (shaded)}$. From the argument above the shaded curve can be translated upwards so that the two I_{sc} measurements coincide. The translation of $V_{oc(shaded)}$ by the same amount gives the point marked with a cross in the figure above. This lies on the IV curve of the cell if there was no R_s.

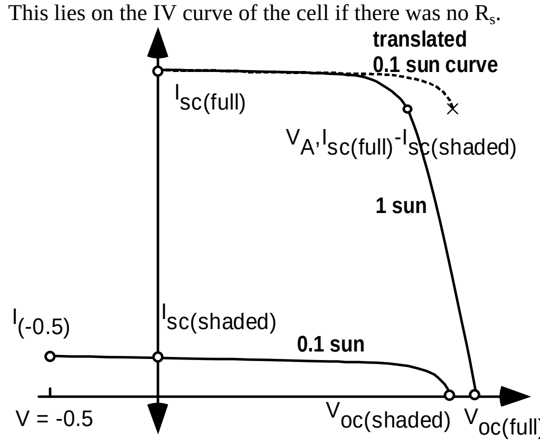

Figure 5: The open circles are the measured data points. The three points on the fully illuminated curve are already measured during the normal IV curve measurement. The only extra data needed for R_s measurement are the cell V_{oc} and I_{sc} under shading. The point in reverse bias is only needed for R_{shunt}.

The series resistance is simply the difference in voltage between the ideal curve and the real curve divided by the current.

$$R_s = \frac{V_{oc(shaded)} - V_A}{I_{sc(full)} - I_{sc(shaded)}}$$

The level of shading only needs to be approximate. The ideal level of shading is $I_{mp} = I_{sc(full)} - I_{sc(shaded)}$ so that R_s is reported at the maximum power point.

5.2. Measurement of R_{shunt}

The shunt resistance is simply the slope of the IV curve in reverse bias, with a reverse bias voltage of 0.5 V:

$$R_{shunt} = \frac{0.5}{I_{(-0.5)} - I_{sc(shaded)}}$$

While it is possible to use the one sun data, the measurement is more accurate in the shaded case since R_s has a smaller effect at lower light intensities and the current difference is more obvious.

5.3. Measurement of the Ideality Factor

The cell ideality factor is defined in a variety of different ways. In this case it is defined as the average ideality factor between the maximum power point (MPP) and V_{oc} and is denoted by n.

Looking at the data of Figure 5 in a different way gives a good measure of the ideality factor from MPP to V_{oc}:

$$n = \frac{V_{oc(full)} - V_{oc(shaded)}}{\ln\left(I_{sc(full)}\right) - \ln\left(I_{sc(shaded)}\right)} \cdot \frac{q}{kT}$$

If n > 1, there is a high junction leakage current due to either a high J_{02} or low R_{shunt}. It is not easy to determine which. An n < 1 indicates a non-ohmic contact, typically an extra diode at the rear contact. By itself n is a useful diagnostic tool.

So long as the level of shading corresponds to about MPP the n factor can be used to determine the fill factor of the cell without the effects of R_s[9].

$$FF_0 = \frac{v_{oc} - \ln(v_{oc} + 0.72)}{v_{oc} + 1}, \text{ where } v_{oc} = \frac{qV_{oc(full)}}{nkT}$$

Since they both describe FF in the absence of R_s, FF_0 should agree with the pseudoFF[7] from SunsVoc measurements. The pseudoFF will be more accurate since it is not affected by temperature fluctuations during the measurement and the shading level does not need to be chosen.

6. KNOWN PROBLEMS

The shading method relies on several assumptions for accurate results. The first requirement is that the cell I_{sc} is proportional to the light intensity. This is easy to test for by verifying that the $I_{sc(shaded)}$ is a constant fraction of $I_{sc(full)}$. If this is not the case it implies that the one sun I_{sc} is affected by R_s. Secondly the temperature of the cell must be stable. V_{oc} is strongly affected by temperature and shading may reduce the cell temperature. The measurement should be done as quickly as possible and a good contact between the block and the cell. At Georgia Tech we use an automated tester and remeasure the cell I_{sc} and V_{oc}.

7. EXPERIMENTAL RESULTS

A screen-printed cell of 100 cm² was measured. The cell has two straight parallel busbars running right across the cell and 5 cm in from the edges. The fingers run at right angles and are also 5 cm long. The cells were first tested by placing a set of probes at the ends of the busbars giving four sets of top contact probes. As each set of contact probes are removed, R_s increases but R_{shunt} and ideality factor stay the same. There is also good agreement between FF_0 and SunsVoc pseudoFF

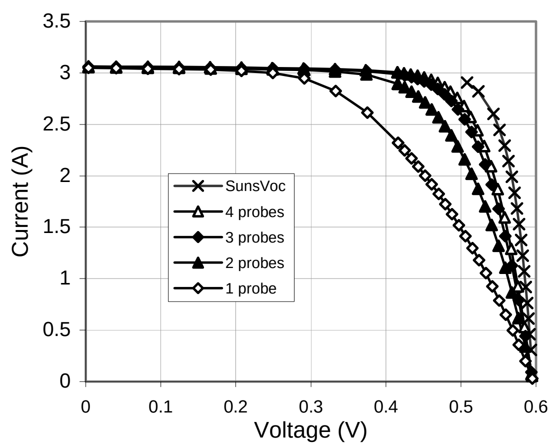

Figure 6: As top contact testing probes are removed the cell R_s increases. The SunsVoc measurement gives the cell IV curve without the effects of R_s.

Probes	FF	R_s Ωcm²	n	R_{shunt} Ωcm²	FF_0	Pseudo FF
4	0.75	1.3	1.09	1341	0.816	0.812
3	0.73	1.7	1.09	1344	0.816	0.812
2	0.67	3.2	1.09	1353	0.816	0.812
1	0.53	6.6	1.10	1344	0.815	0.812

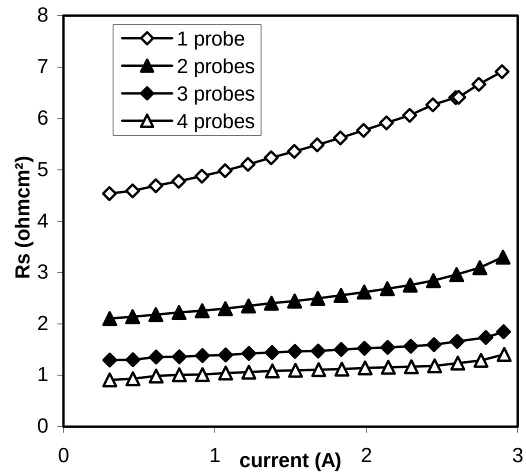

Figure 7: Not only does the cell R_s increase as each probe is removed but the variation on R_s also increases, as evidenced by the increasing slope. R_s is calculated from the difference between the SunsVoc and the illuminated IV curve.

8. CONCLUSION

Distributed effects in R_s can cause the IV curve to look like one with a high ideality factor or one with a low shunt resistance. Guessing if a cell is limited by R_s, R_{shunt} or high J_{02} by looking at the illuminated IV curve has no sound basis. The variation in R_s typically precludes the use of the use of fitting algorithms. Shading the cell to around 0.1 suns and measuring the cell V_{oc}, I_{sc} and current at –0.5 volts reveals a wealth of information about the cell. Even without calibration it provides: the effective R_s at maximum power point, shunt resistance, average diode ideality factor between V_{mp} and V_{oc}, and shows the presence of non-ohmic contacts such as rear surface diodes. Using a calibrated shading also indicates if I_{sc} at one sun is affected by Rs. The technique can be used on existing or automated apparatus with only minor modifications.

9. REFERENCES

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